

Crossovers Between Elastic, Plastic and Quantum Creep in 2D YBa₂Cu₃O₇/PrBa₂Cu₃O₇ Superlattices

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Two-dimensional (2D) vortex dynamics was studied in an YBa₂Cu₃O₇/PrBa₂Cu₃O₇ superlattice by measuring the I-V characteristics. In the high current limit, 2D collective creep was observed with an activation energy characterized by $U(j) \propto j^{-\mu}$. A dislocation mediated vortex melting happened when the temperature increased. In the low current limit, the exponential growth of energy barrier for elastic motion was prohibited by the plastic deformation of vortices. A plateau in the resistive transition was observed, which was attributed to possible quantum tunneling of vortices. Our results suggest that a 2D vortex glass can not exist at any temperature, including T=0 K.

74.60.Ge; 74.76.-w; 74.25.Fy

The unusual resistive and magnetic behavior of high T_c superconductors (HTSCs) has greatly stimulated the efforts to understand the impact of disorder, thermal fluctuations and dimensionality on the vortex dynamics [1]. The theory of collective flux creep describes the thermally assisted motion of vortices in a random potential caused by quenched disorder [2]. Central to the theory of collective flux creep is the elasticity of the vortex system. Due to the finite values of compress modulus c_{11} and shear modulus c_{66} , when moving from one metastable position to another one, the vortices have the tendency to jump in bundles with a radius R_c in order to balance the elastic energy and the energy related to Lorentz force. The energy barrier for activation U_c increases exponentially with a decreasing current because R_c gets larger and larger. However, this picture breaks down when *plastic motion* of vortices is taken into account [3]. For a 2D vortex lattice, due to the finite energy for creation of dislocations or dislocation pairs, a plastic motion of vortices is favorable when the energy barrier exceeds a certain threshold. The plastic creep sets a cutoff for the exponential growth of U_c . The plastic behavior of vortex system has been studied by several groups [4]. Recently, plastic motion of vortices was directly observed on Nb films with artificially introduced pinning centers by using Lorentz microscopy [5].

Quantum tunneling of vortices is expected to replace thermal activation as the dominant dissipation mechanism when the temperature is low enough [6]. Tunneling of vortices has been observed in transport and magnetization measurements [7,8,9,10,11]. It was found that the relaxation rate of magnetization did not extrapolate to zero when the temperature went to zero, and this phenomenon was attributed to quantum tunneling of vortices [7]. Variable range hopping of vortices was observed on ultrathin Pb films [9] and YBCO single crystals with columnar defects [10]. Ephron et al. [11] observed a transition from

thermally activated to a temperature independent resistance on Mo₄₃Ge₅₇ ultrathin films, and this resistance was attributed to the quantum creep of vortices.

Plasticity of vortex lattice (VL) and tunneling of vortices are two possible contributions prohibiting the existence of vortex glass state which is important for future applications. Up to now, they are not well studied and our understanding to these contributions is still limited. This strongly motivates further studies of the interplay between elasticity, plasticity and tunneling of vortices in a 2D vortex system by utilizing suitable samples. In this paper, we report our study of the vortex behavior in 2D YBa₂Cu₃O₇/PrBa₂Cu₃O₇ (YBCO/PBCO) superlattice at different temperature, magnetic field and excitation current. We observed a crossover from collective (elastic) creep to plastic creep of vortices when the elastic limit was reached for a VL, which means a 2D vortex glass can not exist at finite temperature. A dislocation mediated melting of VL was observed in the high current limit. A possibility of quantum creep of vortices at low temperature and thus the non-existence of 2D vortex glass at T=0 is discussed. Our results provide for the first time a comprehensive picture for the vortex dynamics within a 2D VL in artificial superlattices.

The c-axis oriented [YBCO(24Å)/PBCO(144Å)]₂₅ superlattice was fabricated by in-situ magnetron sputtering [12]. The X-ray diffraction showed satellite peak up to the third order, indicating the high quality of the sample. This film was photolithographically patterned into strip with a width of 0.1 mm. DC I-V characteristics were recorded with currents generated by Keithley 238 and voltage detected by Keithley 182. Resistive transition $\rho_{ac}(T)$ was measured by four-terminal ac locking-in technique with an excitation current of 1 μ A at a frequency of 17 Hz. The magnetic field was generated by a 15T Oxford superconducting magnet. During the measurements, the field was kept perpendicular to the film

plane and the temperature stability was better than 10 mK.

Shown in Fig. 1 are the representative I-V characteristics measured at 2 T with the temperature varied from 2 to 32 K. The I-V curves were taken with a temperature interval of 0.1 K. Each I-V curve was obtained by averaging over four individual curves with current applied in positive and negative directions. Two features are clearly visible: (i) *in the high current limit* ($j > 5 \times 10^3 \text{ A/cm}^2$), I-V curves show downward curvature at low temperatures, changing to upward curvature

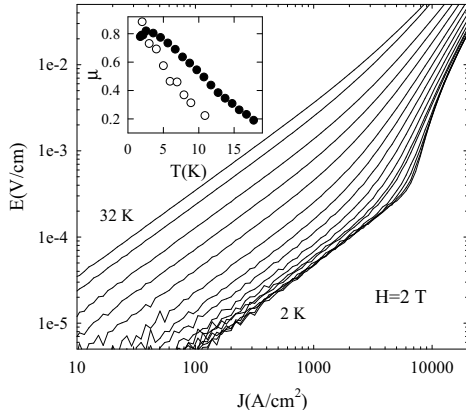


FIG. 1. Selected I-V curves at different temperatures ranging from 2 to 32 K with an interval of 2 K. Inset: temperature dependence of μ at $H=0.5$ T and 2 T, respectively.

at high temperatures; (ii) *in the low current limit*, linear I-V curves were observed for all the temperature region over several order of magnitude for current and voltage. The linear resistivity ρ_L extracted from the I-V curves are shown in Fig. 2 together with the R-T curves $\rho_{ac}(T)$ in the Arrhenius plot. We find that ρ_L coincides with ρ_{ac} quite well. In the high temperature part, a thermally activated flux flow (TAFF) behavior is clearly visible, when the temperature decreases (< 10 K), the resistivity deviates from the TAFF behavior, and reaches a constant value in the lower temperature at each field.

Due to the large PBCO layer thickness, YBCO layers are essentially decoupled, so each YBCO layer can be treated independently. Moreover, each YBCO layer consists of only two unit cells (24 \AA), which is much smaller than L_c ($\sim 100 \text{ \AA}$), the coherence length of vortices along the c-direction. So we treat the whole vortex system as 2D. To understand the above I-V characteristics in the whole temperature and current ranges, we discuss the following 2D vortex dynamics scenarios.

2D collective creep and vortex melting- It is expected that in a 2D disordered superconductor, 2D collective creep of vortices plays an important role in the dissipation process. 2D collective creep theory is applicable when $R_c = a_0(\varepsilon_0 d/U_p)(\xi/2a_0)^2 > a_0 \approx (\Phi_0/B)^{1/2}$, the vortex

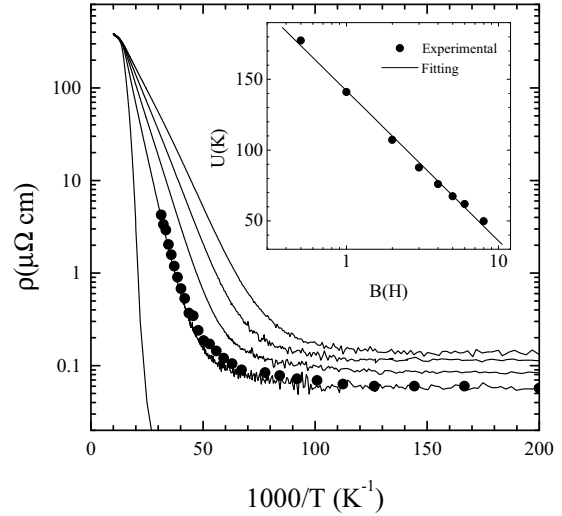


FIG. 2. Temperature dependence of R_{ac} at different applied magnetic field. The solid lines are experimental data. From left to right: $H=0, 2, 4, 6, 8$ T. Filled circles are data points of R_L extracted from the linear parts in Fig. 1. Inset: Activation energies from a TAFF fit to $R_{ac}(T)$, filled circles are the obtained data, solid line is a fitting by $U=141.8-105.9\ln B$.

spacing, where $\varepsilon_0 = \Phi_0^2/16\pi^2\lambda^2$ is the energy for a pancake vortex per unit length, U_p the pinning potential, d the length of the vortex along the field direction, ξ the coherence length [13]. From Fig. 2 we have $U_p \approx 100 \text{ K}$, with $d=24 \text{ \AA}$, $\lambda \approx 1400 \text{ \AA}$, $\xi \approx 15 \text{ \AA}$, $a_0 \approx 500 \text{ \AA}$, and $R_c \sim 5000 \text{ \AA} \approx 10a_0$. Therefore we think that 2D collective creep theory is suitable in the present study. When vortices undergo collective creep, the activation energy is $U(j) \propto (j/j_0)^{-\mu}$, where j_0 is a characteristic current density. Within the TAFF approximation, the I-V curves caused by the presence of the energy barrier $U(j)$ is [2]

$$E = E_0 e^{-\frac{U_0}{kT}(j/j_0)^{-\mu}}. \quad (1)$$

According to Eq. (1), the logarithmic plots of the I-V curves with downward curvature were fitted by a power law, with $\ln E_0$, $(U_0/kT)j_0^\mu$, and μ as fitting parameters. The obtained exponents μ are shown in the inset in Fig. 1. The typical values for $\ln E_0$ and $(U_0/kT)j_0^\mu$ are ~ 10 and ~ 1000 , respectively. The μ values change gradually from 0.8 to 0.2 as the temperature increases. This result agrees well with that of Dekker et al. who found the same trend in the variation of μ upon changing the temperature [14]. We interpret the change in values of μ as follows: as pointed by Vinokur et al. [13], depending on the current density, temperature and magnetic field, the bundle size will be different and consequently μ will take various values. For vortex bundle with medium size (defined by $j_{lb} \approx j_c(R_c^3/\Lambda a_0^2)^{8/15} < j < j_{mb} \approx j_c(R_c/\Lambda)^{8/15}$), an exponent $\mu=13/16 \approx 0.8$ is expected. When $j < j_{lb}$, the

bundle size involved in a jump increases, and the exponent μ changes to $1/2$. We notice that when the magnetic field is fixed, the bundle size is $R_c \propto \xi^2/\lambda^2 U_p$. At temperatures not too close to T_c , where ξ and λ are nearly constants, U_p decreases with increasing temperature, and therefore R_c will increase. As a result, the bundle size will change from medium to large thus decreasing μ value.

As the temperature increases, dislocation mediated vortex melting occurs when the following condition is satisfied: [15]

$$Ac_{66}a_0^2d/kT = 4\pi, \quad (2)$$

where $A \sim 0.4-0.7$ is a parameter due to the renormalization of c_{66} from the defects in the VL and the nonlinear lattice vibration. We identify the melting temperature as the one at which the I-V curves at large current show a power law dependence, i.e., $V \propto I^\beta$. For $H=2$ T, we obtain $V \propto I^3$ at $T=12.87$ K. The shear modulus c_{66} has been calculated by Brandt [16] who showed that

$$c_{66} = [B_{c2}(t)/4\mu_0]b(1 - 0.29b)(1 - b)^2, \quad (3)$$

where $B_c(t)=B_c(0)(1-t^2)$ is the thermodynamic critical field, $t=T/T_c$ and $b=B/B_{c2}(t)$. Inserting the typical values of B_c and B_{c2} for YBCO with $B_c(0) \approx 1$ T and $B_{c2}(0) \approx 100$ T, together with $B=2$ T, $T=12.87$ K, and $T_c=31.5$ K, we obtain $A \approx 0.45$, which agrees well with the previously obtained value [4].

Above the melting temperature, the vortices are in a liquid state pinned by residual forces. The I-V characteristics can be well described by the classic Anderson-Kim model with $E = E_0 \sinh(j/j_0)$.

We notice that Dekker et al. [17] did similar work on ultrathin YBCO films. In their study, only I-V curves with upward curvatures were observed and the glass correlation length ξ_{VG} diverges at $T=0$. They concluded that a 2D vortex glass could not exist at any temperature $T>0$. In our case, we did observe a crossover from downward to upward curvatures. This discrepancy could be possibly due to different length scale involved in the experiments. As we know, when applying a current, a vortex pair of a characteristic size $L_j = (ckT/j\Phi_0)^{1/2}$ is excited [18]. The current probes the vortex dynamics in a length scale of L_j . With $j \sim 5 \times 10^3$ A/cm², $T \sim 10$ K, we get $L_j \sim 1000$ Å $< R_c$. Therefore, we were probing the collective creep behavior in the high current limit. While in their case, the length scale was probably larger than R_c , and thus vortex glass behavior was detected.

Plastic motion in the low current limit- The collective pinning theory depends critically on the elasticity of vortex system. Due to the finite energy for the generation of dislocations or dislocation pairs in a 2D VL, an infinite energy barrier in the elastic limit is not expected. When the energy barrier reaches the characteristic energy for a small dislocation pair, it will be cut off and a crossover from elastic to plastic motion should occur [3].

The motion of dislocation pairs can be well described by TAFF with an activation energy nearly independent of the current density. Therefore, linear I-V curves are expected in the plastic region. As a result, there is no vanishing linear resistivity, and thus *a 2D vortex glass does not exist at any finite temperature. This is exactly what we observed in our I-V curves.* We see that at a current density about $j \sim 5 \times 10^3$ A/cm², the I-V curves with downward curvature change to linear at low current densities. This linearity is valid in the range of more than two orders of magnitude in the current and voltage. The typical energy for a dislocation pair made up of two edge dislocations separated by a_0 is [3]

$$U_e = \frac{\Phi_0^2 d}{16\pi^3 \lambda^2(T)} \ln(B_0/B), \quad (4)$$

With $\lambda \approx 1400$ Å, we have $U_e \approx 500$ K. This is consistent with what we have obtained from a fitting to the I-V curves we made earlier. With $(U_0/kT)j_0^\mu \sim 1000$, $j_0 \sim 10^5$ A/cm², we have $U_0 \sim 300$ K, which agrees quite well with U_e . This explanation is further supported by the $\ln B$ dependence of activation energies which were extracted from the slopes of the Arrhenius plot as shown in Fig. 2. So we conclude that *in the low current limit, the dissipation is governed by plastic motion of dislocation pairs in the VL.*

The above picture is consistent with Monte Carlo simulations of the VL subject to random disorders under a driving force [19]. It is found that at large driving force, the vortex motion is elastic. As the driving forcing force decreases, the VL becomes defective, and the dissipation is dominated by plastic motion.

Possible quantum tunneling of vortices at low T- as we can see from Fig. 2, below $T \sim 10$ K, the resistivity gradually deviates from the activated behavior, showing a level off toward constant values [20]. The resistivity at the plateau grows with the increasing magnetic field. To get such a plateau within the framework of TAFF would require an activation energy U_0 which increases linearly with T , i.e., $U_0 \propto \alpha T$. We are not aware of any mechanism that can provide such kind of an activation energy. Same resistive plateau in the R-T curves was also observed by Ephron et al. on Mo₄₃Ge₅₇ thin films.

Generally, it is believed that quantum tunneling, if it does exist, dominates the dissipation at temperatures below several Kelvin and that the resistivity from a quantum creep is nearly independent upon temperature [21,22,23,24]. We are not sure why we observed quantum tunneling behavior at such a high temperature where the thermal energy of vortices is quite high. One possibility is a large normal resistivity ρ_n and a small coherence length ξ . The tunneling rate γ is determined by the effective Euclidean action S_E^{eff} for the tunneling process, $\gamma \propto \exp(-S_E^{eff}/\hbar)$, and S_E^{eff}/\hbar in turn is proportional to $(\hbar/e^2)\xi/\rho_n$ [21]. Therefore, tunneling is favored by a

small coherence length ξ and a large normal state resistivity ρ_n . Experimentally, Ephron et al. reported that they were only able to observe such a plateau on thin films with large sheet resistance, this is consistent with theoretical consideration.

The existing results on the temperature T_0 at which the dissipation shows a crossover from thermally activated to a quantum tunneling range from hundreds mK to tens Kelvin. Ivlev et al. [22] showed that, for YBCO compound, a crossover from thermally activated to quantum tunneling dissipation happens at $T_0 \approx 50(j_c - j)^{1/2}/j_c^{1/2}$ K. Meanwhile, Stephen [23] found that $T_0 \approx 2$ K. Experimentally, a crossover temperature ranging from 3.5 K to 10 K was reported for TlBaCaCuO single crystals [8]. When vortices are localized by columnar defects, a crossover temperature from collective creep to quantum creep (variable range hopping) as high as 35 K was reported in the high current limit ($\sim 10^6$ A/cm²) [10]. It is worth noting that Blatter et al. [21] found the suppression of the tunneling rate for increasing field. In this case the interaction between vortices increases, the viscosity grows and more vortices are participating in a single tunneling event. This is consistent with our observations. We found that the temperature, at which the resistivity starts to deviate from TAFF behavior, decreases with the increasing magnetic field.

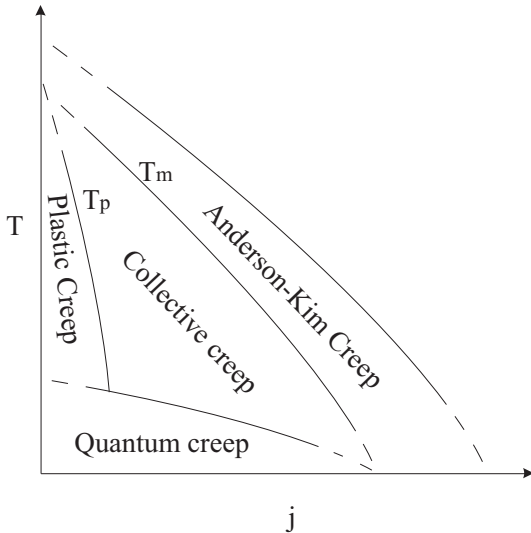


FIG. 3. A schematic j - T phase diagram for a 2D VL at a certain magnetic field. The line T_m is determined by Eq. (2), and line T_p by Eq. (4). In the quantum creep and plastic creep regions, the linear resistivity does not vanish. The collective creep and Anderson-Kim creep regions are characterized by I - V curves with $E \propto e^{j-\mu}$ and $E \propto \sinh(j/j_0)$, respectively.

Therefore, our results suggest the possibility of tunneling of dislocation pairs which are equivalent to a vacancy

or an interstitial in a VL, and a 2D vortex glass can not exist even at $T=0$ K. At present, due to the lack of a suitable theoretical model, we are not able to do a quantitative analysis of the appearance of the puzzling plateau in the low T region. Further theoretical and experimental work at that subject is greatly encouraged.

The main conclusions of this work are summarized in fig. 3. We found that the vortex dynamics is essentially length scale dependent. In the high current limit, 2D collective creep was observed which is elastic in nature and characterized by an energy barrier with an exponential growth with current density. The 2D VL undergoes a dislocation mediated melting at a temperature T_m . In the low current limit, the exponential growth of energy barrier is cut off by the generation of dislocation pairs in the VL and their subsequent motion or quantum tunneling. The linear resistivity at low temperatures ($\lesssim 10$ K) is possibly governed by quantum tunneling of pancake vortices. With increasing Lorentz force, the driven VL recovers its elasticity at high current density.

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